NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report No. 32-785

A Lunar and Planetary Petrography Experiment

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Alden A. Loomis

R. H. McFee, *Manager*
Lunar and Planetary Sciences

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ABSTRACT

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A preliminary model of a petrographic microscope for lunar and planetary missions has been fabricated. It is designed primarily for remote operation on soft-landing spacecraft, but could be adapted for support of a manned mission. The sample is not a thin section, but an aggregate of crushed rock particles. The image is projected from an air-gapped 16X refracting objective lens through interchangeable eyepiece lenses onto the faceplate of a television camera. The sample particles are thermally encapsulated between two opposing sheets of a clear isotropic thermoplastic ($n = 1.54$). A television picture is taken both below and above the plane of correct focus as well as in that plane for each field of view in order to change the Becke line positions. Each grain is viewed in both plane-polarized and cross-polarized light; the spectral width is small enough to provide dark and light interference rings on a black-and-white TV. The primary use of the microscope is observation of rock textures. Secondary uses are determination of bulk mineralogy, observation and compositional estimation of glass, identification of phases which occur in small amounts, and identification of the different rock or mineral types in an originally particulate sample.

author

I. NATURE OF THE EXPERIMENT

The most commonly used geological laboratory technique for observing, categorizing, and genetically interpreting rocks is the microscopic observation of both the mineral assemblages of the rocks and the geometrical relations among the mineral grains. The main utility of the microscope here is to observe rock texture—the sum total of the intragrain and intergrain relationships within the rock. The standard laboratory preparation procedure for a cohesive rock is to attach a slab of rock to a glass slide and grind it until it is uniformly about 30 μ thick, at which point nearly all rock-forming minerals are transparent or translucent. A *thin section* produced in this way displays the rock in a two-dimensional pattern which shows the relative shapes and sizes of different mineral crystals and the geometrical relations of the crystals of one mineral with those of the others.

Making a standard petrographic thin section is an exacting and painstaking process, however, and should not be attempted in a remotely operated experiment on the surface of the Moon or other planet. Furthermore, a thin section can only be made from a cohesive rock. The instrument to be described in this report utilizes a particulate sample and encapsulates the particles in a transparent medium for transport and for viewing with the objective lens. The data are inferior to those obtainable from thin-section observation, but a great deal of valuable information of a basic nature should be available for almost any sample. The maximum amount of information can be obtained from particles in the 50- to 300-μ size range. Particles of that size are most common in the illustrations of this report. If the mineral crystals are much smaller than the rock particles themselves, the crystals will interfere with one another optically and the particles will be less transparent than those consisting of single mineral crystals.

A petrographic microscope differs from ordinary biological microscopes in that it utilizes cross-polarized, as well as plane-polarized, light in order to achieve certain interference effects. The optical and physical properties of the common rock-forming minerals serve to distinguish them from one another; the bulk mineral assemblage can be determined by statistical counting within the thin section. Rocks are classified both in terms of texture and mineral assemblage, and an experiment which can provide both types of information is of considerable importance.

Fig. 1. Little Lake basalt, plane-polarized light
Lath-shaped plagioclase crystals are aligned in a flow fabric

Polycrystalline particles can be recognized as such in most cases, and although most individual minerals may be difficult or impossible to identify, we at least will know that we are dealing with a fine-grained rock and we may be able to see some of the intergrain relationships. The particles in Fig. 1 are good examples of this.

Two cases in which it would be possible for the experiment to yield relatively little information are if the only material available near the surface is dominantly fine-grained, say less than 20 μ, or if the particles near the surface are darkened or stucturally damaged by solar emanations.

A microscope is unique among analytical instruments in that it provides observations of individual mineral or rock grains. Other chemical or mineralogical experiments provide a bulk analysis of any given sample which may contain many thousand individual grains. Such bulk analyses are generally adequate for a crushed bedrock sample because all particles were part of the same rock. However, the individual component grains of a mechanically aggregated particulate sample are likely to be of considerable importance in determining the distribution of rock types in the surrounding area and the manner of mixing of surface materials. The ability to analyze meaningfully a loose surface aggregate of particles is especially important during the early unmanned phases of exploration when sample-acquisition devices are a major engineering problem. For example, the surfaces of both Mars and the Moon may be covered in many places with particulate debris which is too deep (more than one-half meter or so) to be reached by a remotely operated spacecraft drill. In that event, we will have to deduce from the surface mantle what we can of the bedrock type at that location, the nature of the bedrock at more distant locations, and whether the surface particles were moved to that place dominantly by meteorite impact, by volcanic explosive activity, by running water, or by wind. (Although only the first two of these processes apply to the Moon, all apply to Mars.)

II. OBJECTIVES OF THE EXPERIMENT

Knowledge of the lateral and vertical distribution of rock types at the surface of a planet is of first-order importance in deciphering the physicochemical history of both the body and the surface of the planet. The evolution of a planet is recorded largely in its rocks. The nature of the rocks and rock sequences indicates something about the thermal history of the body, the nature and degree of internal strains, and reveals the processes active near the surface.

For example, if igneous rocks are extensively distributed at the surface, much internal melting has occurred. The mineralogical and chemical variations within sequences of volcanic rocks provide information on the extent and nature of gases associated with the rocks.

The objectives of the lunar and planetary petrography experiment are to delineate as specifically as possible the nature of the processes which have operated on a given planetary body. The experiment is designed:

1. To observe rock textures.

2. To determine the gross mineralogical character of the sample and identify phases which occur in small amounts.

3. To detect the presence of glass and estimate its composition.

4. To determine the size and shape distribution of particulate surface materials.

The microscope design as it now stands provides for encapsulation of crushed rock particles in a thermoplastic mounting medium of known refractive index. The particles are viewed in both plane-polarized and cross-polarized monochromatic transmitted light. Vidicon images are recorded at several points of focus within the sample layer.

III. INSTRUMENT DEVELOPMENT

A. Background

In 1961, a subcontractor was funded for design and fabrication of a breadboard microscope under Contract No. 950146. The details of that development are listed in the final report which was submitted May 31, 1963.

Subsequent development has been at JPL under the direction of Dr. A. Loomis. An entirely new breadboard was designed and fabricated during fiscal 1964 and 1965; work on a hopper and sample screen is still proceeding in April, 1965.

B. Instrument Description

The microscope includes the following four subsystems.

1. The sample-handling subsystem consisting of
   - (a) a mechanical hopper,
   - (b) a particle-immersion mechanism, and
   - (c) a rotating stage.
2. The substage optical subsystem consisting of
   - (a) a light source,
   - (b) a narrow-band (10 mμ) filter at about 550 mμ (set to match peak spectral response of vidicon),
   - (c) a polarizer, and
   - (d) a substage condensing lens.
3. Objective subsystem consisting of
   - (a) an objective lens,
   - (b) a step-focusing mechanism, and
   - (c) interchangeable or removable eyepiece lens(es).
4. Imaging subsystem consisting of
   - (a) neutral-density filters and analyzer and
   - (b) a vidicon tube.

The entire assembly excluding the vidicon tube is shown in Fig. 2. The assembly as shown, without external electronic controls, weighs 8 lb. A prototype instrument with controls should weigh about 5 to 8 lb. A vidicon tube weighs about 9 lb, so a complete flight instrument should weigh about 15 lb.

1. Sample-Handling Subsystem

The sample-handling subsystem was by far the most complex and troublesome part of the instrument. Figure 3 shows the fabricated model. The function of the sample-handling mechanism is to accept a crushed rock powder, immerse it in a suitable mounting medium, and transport it to a position where it can be viewed by the objective lens. The present design encapsulates the rock particles between two glass slides which are coated with a thermoplastic. Figure 4 demonstrates the encapsulation schematically. An extensive program of testing thermoplastic immersion media has been completed. Zerlon, a methylmethacrylate styrene copolymer made by the Dow Chemical Company, has been found to have suitable thermoplastic properties as well as optical stability in 40-day tests at elevated temperature in vacuum. A report of the test program is given in Ref. 1.

The general operating procedure is as follows. The sample is dropped in the hopper and vibrated through an appropriate screen onto a flexure-mounted elastomer pad contained on the lower disk. (The hopper can be emptied and cleared for the next sample by rotating approximately 150 deg around a horizontal axis.) The lower disk is rotated 30 deg to the clamp station. A scraper attached to the hopper removes excess sample during rotation. The pad has a textured surface which retains a layer of sample. The clamp presses the elastomer pad against a Zerlon-coated glass slide in the upper disk. The jaws of the clamp each contain a heater; they heat the 0.030-in.-thick plastic coating on the glass slide to approximately 310°F, softening the plastic to allow the sample to be partially embedded, thereby transferring a monolayer of sample from the pad to the plastic. The clamp is released and a second plastic-coated slide contained in the bottom disk is brought to a position under the top slide by a 30-deg rotation of the bottom disk. The clamp is again actuated and the lower slide is ejected from the lower disk and pressed against the upper slide. The clamp jaws are heated to 375°F to complete sealing of the sample particles between the lower plastic-coated slide and the top plastic-coated slide. The upper disk with the encapsulated sample is then rotated 30 deg (after lifting hopper) to the microscope station for viewing. One pulse of the stepping motor drive moves the slide approximately 1½ mm, allowing 20 viewing positions per slide. Either the gearing or the motor can be changed to allow more viewing positions. The entire procedure is repeated for each additional sample.

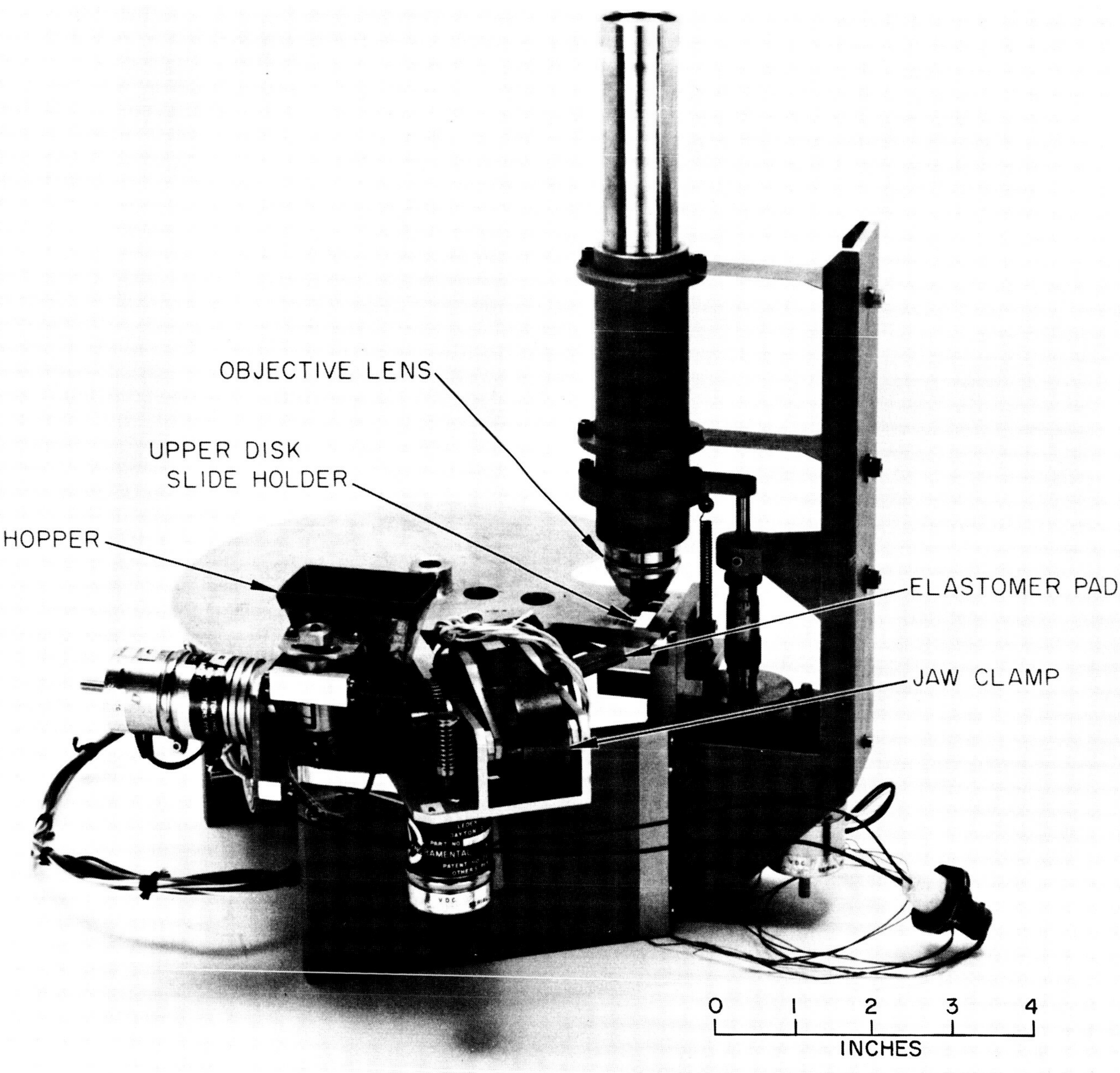

Fig. 2. Breadboard model

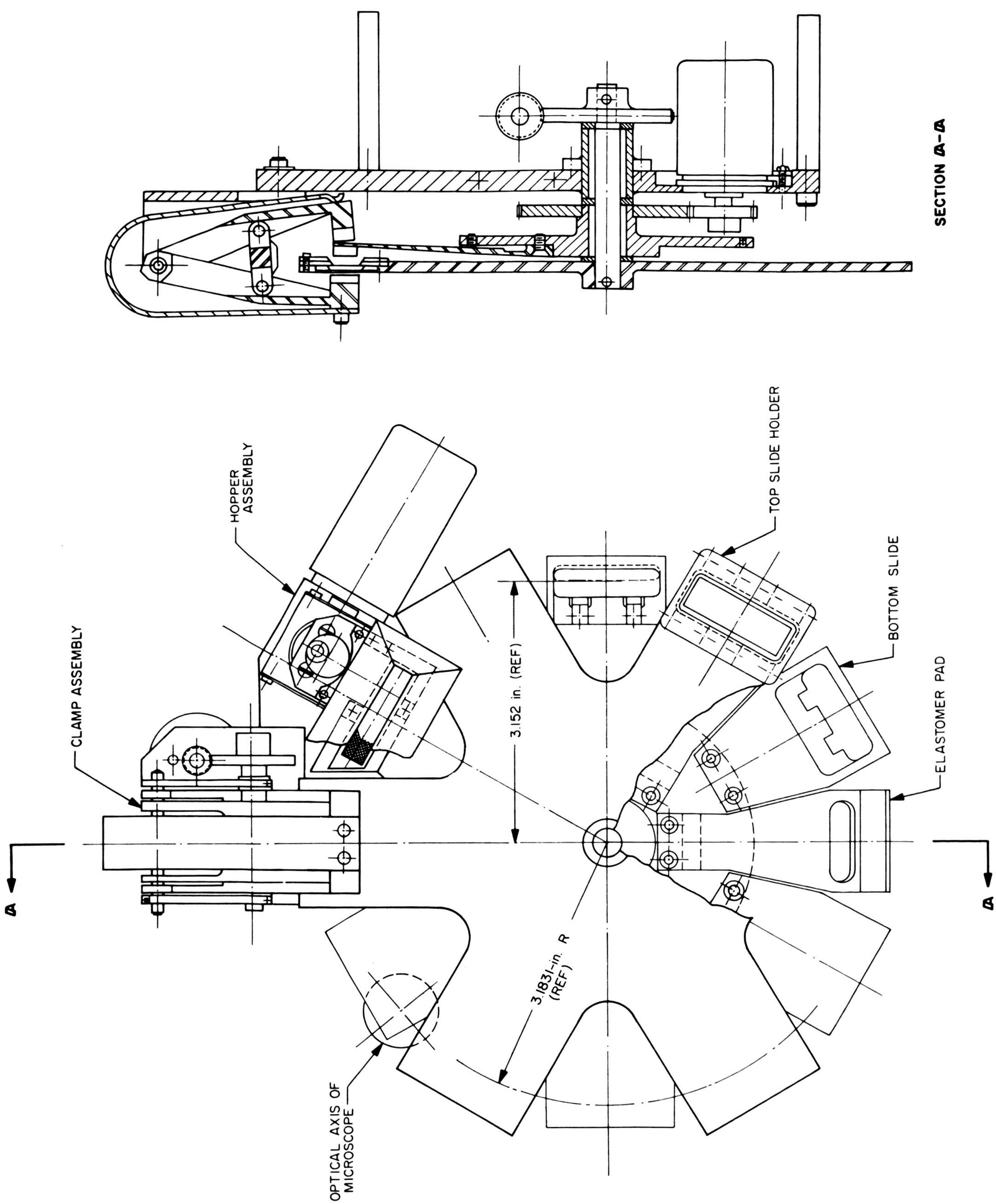

Fig. 3a. Sample-handling subsystem design

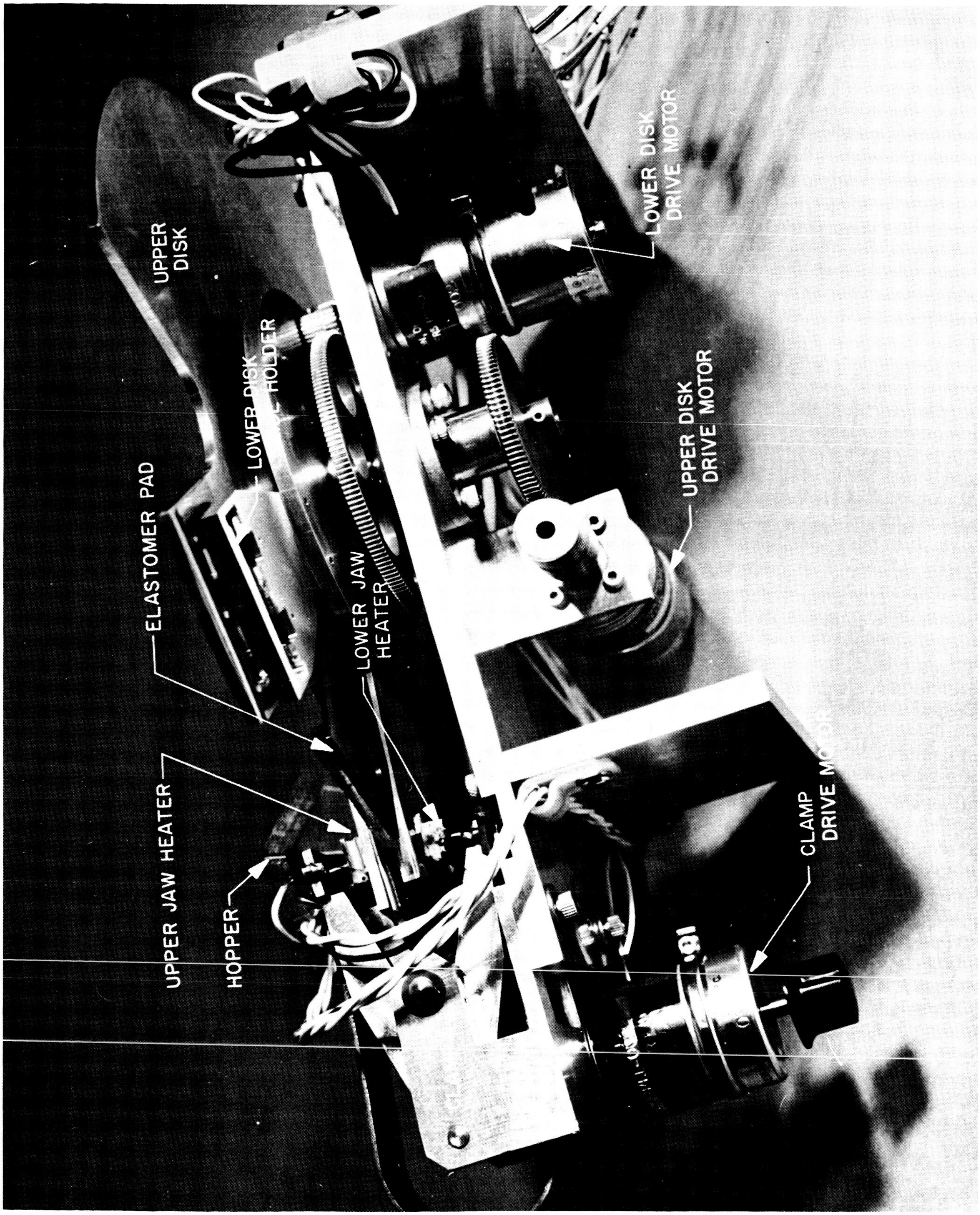

Fig. 3b. Sample-handling subsystem breadboard

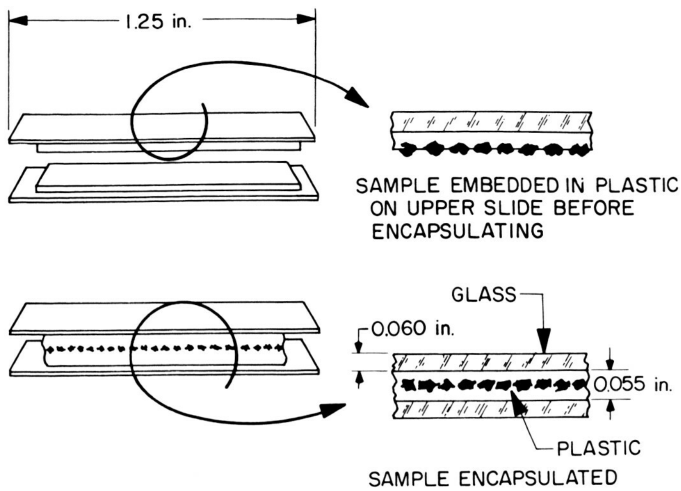

Fig. 4. Schematic diagram of encapsulation procedure

The heater on the lower jaw of the clamp has a resistance of 110 ohms and dissipates about 5 w at 22 v. The heater on the upper jaw has a resistance of 140 ohms and dissipates about 3½ w at 22 v. The time required during operation in vacuum to soften the plastic in order to transfer the rock particles from the elastomer pad is about 3 min; about 4 min are required to bond the two plastic faces together and fully encapsulate the sample. Full voltage is not used during the entire heat-up time, however. The total work done during the encapsulation is therefore about 1 w-hr.

Some elastomer pads were found to be unsatisfactory because they outgassed badly during heating. Pads made of the silicone Sylgard 184 have been satisfactory.

The breadboard model is capable of processing six separate samples. The samples are placed with their long axes in a tangential position to the disks so that the rotation mechanism for the disks can serve as the scanning mechanism during the viewing sequence. A much more compact model could be built either if fewer samples were used, if the disk were capable of a translation direction relative to the objective lens other than simple rotation, or both. Many configurations are possible which will be much more resistant to vibration and shock damage; the final design for a prototype has not yet been selected.

The breadboard hopper contains a screen which retains particles larger than 300 μ. The hopper vibrates and depends upon gravity to move the particles through the screen. Because it is feared by many that fine particles will adhere to one another and to the meshes of a sample screen on the Moon, a more positive action is desired. Such a mechanism is being designed and fabricated during the last quarter of Fiscal 1965; test results are unavailable as of this writing.

Particles with diameters greater than the thickness of the two Zerlon sheets must be screened from the sample or else they will hold the glass slides apart during encapsulation and make the encapsulation ineffective over much or all of the slide. A 300-μ sieve is being used at present because particles much larger than 300 μ commonly are too thick to provide much scientific information. If we should later anticipate that electrostatic or cold welding forces are strong relative to the mass of 300-μ grains, the coarse screen could easily be set to admit grains of 1-mm diameter or larger and still retain the same encapsulation procedure.

The positive-action hopper and screen assembly presently being designed will not only separate large particles from the sample but will divide the remaining grains into the two size groups, 0 to 60 μ and 60 to 300 μ. The main reason for such a separation is that much more textural and mineralogical data are available from the larger particles than from the smaller and the smaller particles would tend to optically obscure the image of the larger ones. In the event that all particles from the sample came from the same crushed bedrock sample, the only effect would be to bias the sample somewhat because some minerals crush to fine sizes more easily than others. Such a bias would not be serious and the fine particles would be discarded.

If, however, the sample was from a particulate surface layer, the finer size range would probably contain most of the micrometeorites and should yield important information. In this event, both size fractions would be encapsulated separately. A prototype model will be fabricated in Fiscal 1966 which can handle four samples; these could be both the coarse and the fine fractions from each of two particulate samples or those two fractions from a particulate sample and one or two bedrock samples.

Figures 1, 5, 6, 7, 8, and 9 all show grains in the 60- to 250-μ size range; these figures illustrate the large amount of information available in this particle size, especially when the particles are not obscured by finer grained material.

2. Substage Optical Subsystem

The substage optical subsystem contains a light source, a narrow-band filter, a polarizing filter, and a condensing lens. A standard six-volt incandescent bulb is being used for the breadboard with a Baird-Atomic interference filter. An interference filter must have a half-width of less than about 14 mμ in order to produce sharp interference bands on a black-and-white TV. The wavelength desired from the scientific point of view can be anything shorter than about 530 mμ and which is compatible with the peak response of the imaging system employed. The General Electrodynamics Corporation vidicon which has been used with the breadboard has a peak spectral response at 550 mμ.

The polarizer has been made of Polaroid Corporation's KN-36, a neutral linear polarizer on a polyvinyl alcohol base. Sheets of KN-36 have been treated and cooled in moderate vacuum ($\sim 10^{-6}$ torr) in partial lunar environmental tests. The KN-36 sheets in cross-polarizing position polarize very effectively in the 500- to 550-mμ range but not nearly as effectively in blue or red wavelengths.

The condensing lens can be a single biconvex element which produces an apical angle of about 20 deg. This convergence is not meant for conoscopic observation; it is only to increase the surface relief of transparent particles in the sample and to enhance the Becke line effect. (See Sections IV-B and IV-D.)

3. Objective Subsystem

The objective subsystem includes the objective lens, step-focusing mechanism, eyepiece lenses, and the optical tube between the objective lens and the faceplate of the imaging subsystem. It is desirable

(a) to be able to change magnification at will, say between 25X and 100X,

(b) to not refocus the objective lens with each magnification change,

(c) to maintain a long working distance with the objective lens, and

(d) to keep the vidicon or other imaging system in a fixed position.

One possible method of attaining such objectives is to have a zoom-type objective lens. Another is to have alternative eyepiece lenses between the objective and the imaging faceplate; this second method seems most practical at this writing.

A focusing capability is required in order to see particles whose tops are above or below the pre-set zone of focus of the lens and also for the observation of Becke line motions (Section IV-G). A slow-scan TV system must image an effectively stationary object and the simplest method seems to be to have the focus change between TV pictures in a series of discrete programmed steps.

4. Imaging Subsystem

The imaging subsystem includes a television camera or other camera and the necessary auxiliary electronics, and a polarizing filter (the analyzer) whose plane of polarization is placed at right angles to that of the substage polarizer. Each particle in the field of view must be seen in both plane-polarized and in cross-polarized light. The present breadboard has the field of view split so that one half is plane-polarized and the other half is cross-polarized. The indexing movement of the sample is one-half of the field of view, thus allowing each particle to be seen with each type of light. A neutral density filter is used in the plane-polarized half of the field in order to make the peak intensities similar in both sides of the field.

A slow-scan vidicon was purchased from the General Electrodynamics Corporation as part of the original breadboard model. Several of the figures of this report are photographs of an image on the monitor of that set. The focus is not good at the edges of the raster when the central focus is sharp; this is the fault of the TV system and not of the microscope optics and could be easily remedied.

The electron optics in the vidicon system determine the resolution of the final images. The diameter of the scanning spot in the vidicon tube is about 25 μ and probably cannot be made smaller. The desired final resolution therefore determines the total optical magnification to be used before the image is displayed on the vidicon faceplate. As an example, in order to determine the shape of a grain, eight to ten separate scans across the grain must be made. Because the scanning spot is 25 μ wide, the image on the faceplate must be 200 to 250 μ across. If the actual size of the grain is 10 μ, the optical image magnification must be 20X to 25X.

The vidicons now available have erasure times of about three to four seconds. There is no need for the light source to emit light except when exposing the television faceplate; a pulsed light source could operate as the shuttering mechanism for the television system.

5. Power and Data-Rate Requirements

The peak power and total requirements of a flight model microscope can be estimated roughly. The peak power required to operate the stepping motors is about 40 w in pulses of 40 msec duration; only one motor operates at a time. The peak power required to encapsulate the sample is about 8 w for the heaters. The power required to operate an incandescent light source would be about 2 w and would be fairly constant; a spark source would require higher peak power but probably less average power. The total power required to encapsulate one sample and move it to the field of view of the objective lens is about 2 w-hr. The total power required to obtain TV images and read them out prior to transmission to Earth depends upon the type of mission; for the Moon it is about 12 w average power. The bandwidth available to lunar missions will be about 250 kc, which is about enough to transmit one 600-line TV frame per second. The power required for transmission to Earth is about 50 w peak input power; images can be obtained about once every four seconds meaning that the average power required for transmission is about 13 w.

A lunar operation on an unmanned lunar soft-landing mission would entail encapsulating four samples and obtaining about 2000 TV pictures (five pictures at different focus levels per field of view, 100 fields of view per sample, four samples). The time necessary to fractionate and encapsulate the samples will be about 15 min per sample, or 1 hr total. A picture is transmitted in 1 sec; we therefore need 2000 sec of transmitting time. The time between successive pictures depends upon the erase and readout times of the camera. During the erasure time for the microscope camera, data from other experiments could be transmitted. On these bases, the total operation time for an unmanned lunar microscopy experiment would be three to four hours plus whatever extra time might be dictated by the quality and interest of the data. The total power expenditure would be 40 to 50 w-hr.

An operation on Mars would be different because of the low power and bit-rate levels on planetary missions. Using *Mariner IV* TV as an example, a 200×200-element format is used; each of the 40,000 picture elements is assigned one of 64 discrete levels of luminance. A binary representation for numbers to 64 requires six bits of information per number. A digital signal of 240,000 bits is therefore required for each picture. At a bit rate of about 8 bits per sec, a picture could be transmitted in 8 to 9 hr which is about two-thirds of a transmitting day from Mars. A surface capsule should have a lifetime of several weeks to months, so that 10 to 20 pictures might be adequate. In this event, a lens with a large depth of focus would be employed and only one picture taken per field of view.

IV. OPTICAL PRINCIPLES AND TECHNIQUES INVOLVED

A. General

The following discussion of the useful optical phenomena produced by this microscope is very brief. It is only intended to aid the reader in understanding the interpretation of microscopic images presented later in this report. More complete presentations are available in standard crystallography textbooks (e.g., Ref. 2).

This microscope has been designed only to magnify an object on the stage. The total magnification is variable, depending upon the optical path length between the objective lens and the vidicon faceplate. The most useful single magnification is about 25X. The light train passes through, in order: narrow-band filter, condensing lens, polarizer, object, objective lens, analyzer (eyepiece).

B. Refractive Index

The refractive index of a substance in any given vibration direction is the ratio of the velocity of light in vacuum to the velocity of light in that substance. Most crystals have slightly different refractive indices in different vibration directions. Instead of comparing the refractive index of an unknown crystal with that of a vacuum ($n = 1$) in the lunar petrographic microscope, it is compared with that of the thermoplastic mounting medium, which is 1.54.

If a transparent crystal has the same refractive index as the mounting medium it will be invisible or nearly so. As the difference between the two indices increases, both the outline of the crystal and any protuberances on its surface become more and more visible because strong edge shadows are produced by total internal reflection. The shadowed texture of a crystal is termed "relief." Figure 9a shows grains with low relief; the difference of indices between them and the thermoplastic is 0.03. The large transparent grain in Fig. 1 shows high relief; the difference of indices between it and the thermoplastic is 0.16.

C. *Interference Phenomena*

When a ray of light enters a mineral grain on the stage, it is split into two components which vibrate parallel to two of the principal optical directions within the crystal. The direction of vibration of each component is perpendicular or nearly perpendicular to the direction of propagation of the light, which is the ray direction.

In general, a path difference is produced between the two components because the refractive indices within the crystal are different in the two vibration directions, and one component therefore travels more rapidly through the crystal than the other. Isometric crystals and amorphous substances (e.g., glass) produce no path difference. In tetragonal and hexagonal crystals there is only one direction of propagation in which all vibration planes have the same velocity and no path difference is produced. In monoclinic, orthorhombic, and triclinic crystals there are two such directions.

When the mineral grains are viewed without a second polarizing filter (the analyzer) in the light path, they appear essentially as they would in unpolarized transmitted light. With the analyzer, whose plane of polarization is set at 90 deg to that of the substage polarizer, in place, the two components are resolved. Constructive or destructive interference takes place, depending upon the extent of the path difference which was produced by the crystal. The amount of path difference is a function of the difference of refractive indices in the two vibration directions, the thickness of the crystal, and the wavelength of light used.

In monochromatic light, all points on the crystal that mark the emergence of light components which interfere constructively are illuminated; points of emergence of components which interfere destructively are dark. Any fractional path difference produces some illumination and the illumination decreases to zero as the path difference approaches a whole number. Sequences of bright and dark rings on olivine grains are shown nicely in Fig. 6b. If the crystals were flat plates, their tops would either be uniformly bright or uniformly dark. The bright and dark bands are caused by the increase in thickness of the crystals toward their centers; the thicker the crystal, the greater the path difference. For crystals of any given thickness and orientation, the number of bands is proportional to the difference in refractive indices in the two vibration directions of the light. This index difference is termed birefringence; its magnitude is an important diagnostic property of minerals.

D. *Becke Line and Central Illumination*

The Becke line is an optical effect which is used to determine whether a crystal has a refractive index above or below that of the mounting medium. The strength of the line is an indicator of the magnitude of the difference between the indices of the crystal and the medium.

Crushed mineral fragments tend to be lenticular. The edges of such fragments which have a higher refractive index than the mounting medium refract the incoming light inward, toward the center of the crystal. A concentration of light, known as the Becke line, rims the crystal and lies within its edges. Because the light emerging from the top of the crystal is converging, the concentration of light appears to move inward from the edges of the crystal as the objective lens is lifted above sharp focus.

The effect is just reversed if the crystal fragment has a lower refractive index than the mounting medium. In that case the edges of the crystal refract the light away from the center of the grain; the Becke line moves progressively farther into the mounting medium as the objective lens is raised above sharp focus. Figure 9 illustrates the effect.

E. *Textural Observation*

The most important factors in a genetic interpretation of a rock are texture, mineral assemblage and chemical composition of the minerals, and time of crystallization or accumulation of the rock relative to other rocks in association with it. Rocks are classified primarily on the basis of the first two of these, texture and mineral assemblage. The most commonly used major categories are based almost entirely on texture and are as follows:

1. Igneous
    a. Volcanic.
    b. Plutonic.

2. Sedimentary

   a. Mechanically accumulated clastic.

   b. Chemically precipitated from solution at planetary surface.

3. Metamorphic

   a. Recrystallized without major chemical change.

   b. Replacement with chemical change.

Most subdivisions of rock types within these groups are made on the basis of mineral assemblages and relative proportions of certain minerals. Using igneous plutonic (coarse-grained) rocks as an example, they are found statistically to fall in several groups: those with more than 10% quartz, those with less, and groups containing the feldspathoid minerals. Rock names within these groups are assigned on the basis of relative proportions of the most common minerals in the rocks—feldspars and feldspathoids, pyroxenes, and olivine. Bulk mineralogical data are therefore needed to determine rock types within the broad textural classifications. Mineral chemical composition and the relative abundances of the major phases can be used to compute an approximate chemical analysis of the bulk sample. The reverse process—calculation of the mineral compositions and abundances from a chemical analysis—always must be done under assumptions about the conditions of formation, usually that the mineral assemblage formed in chemical equilibrium and not, for example, as a mechanical mixture of accumulated particles. Knowledge of both rock texture and bulk mineralogy are therefore essential for a genetic interpretation of an unknown rock.

The textural distinctions required for the separation of rocks into the broad categories are for the most part simple. Igneous rocks are those which generally contain many euhedral crystals of certain minerals; well-formed crystal faces, particularly on quartz and feldspar grains, indicate that the crystals formed freely in a liquid medium. Rocks which are mostly fine-grained but which may contain several percent coarser grains show evidence of having cooled quickly although some grains may have crystallized under more stable conditions; this is the classic volcanic texture. Figure 1 is a photograph of a slow-scan TV monitor showing crushed particles of a basalt which illustrates the important textural features. The large grain is olivine; the small clear rectangular grains are plagioclase feldspar. Igneous rocks which are relatively coarse-grained cooled more slowly at depth; an average grain size of about 0.5 mm separates most volcanic from most plutonic rocks.

Plutonic igneous rocks are most commonly separated from high-grade metamorphic rocks which contain the same minerals on the basis of the degree of compositional zoning and crystal perfection of the feldspars and quartz, or simply on the basis of field-relationships. The euhedralism of coarse plagioclase grains probably will be impossible to assess in crushed grain mounts, but extreme compositional zoning might be detected.

Lower-grade metamorphic rocks contain minerals which are uncommon in igneous rocks. However, the identification of most of the common low-grade metamorphic minerals such as serpentine, chlorite, epidote, and glaucophane possibly will be quite difficult because of their fine grain size and their common intertwining habit. The distinction between plutonic igneous and metamorphic rocks may be difficult or impossible to make by remote observation of crushed grain mounts.

Accumulated (sedimentary) rocks are separated from both igneous and metamorphic rocks by their particulate nature. Also, because they are mechanically mixed aggregates, they may contain minerals which could not have crystallized together in equilibrium. If the particles have been transported in a moving fluid medium they will be more or less mechanically rounded, whereas if they have been merely dropped into place after disintegration they will be quite angular.

F. Mineralogical Determination

Many individual mineral grains normally can be identified in each grain mount. Enough grains should be identifiable in any specimen to determine the rock type unless the crystals have suffered extensive damage from corpuscular radiation or are too fine-grained to permit identification. The distinguishing features of minerals viewed in monochromatic transmitted light are:

1. crystal form
2. type of cleavage
3. mean refractive index
4. birefringence (difference between highest and lowest refractive indices)
5. transparency.

Fig. 5. Del Puerto Canyon pyroxenite, plane-polarized light

The olivine phenocryst in Fig. 1 can be identified as olivine because it has a high refractive index relative to that (1.54) of the mounting medium, shows no cleavage, and has good transparency even when over 50 μ thick. The plagioclase grains in Fig. 1 can be identified on the bases of their rectangular shapes and their refractive index which is close to that of the mounting medium.

The grains in Fig. 5 are pyroxenes; they can be distinguished from olivine because the pyroxenes have good prismatic cleavages. The pyroxenes can be distinguished from amphiboles because of their transparency, even in large grains.

Figure 6 illustrates one use of birefringence in mineral identification. Figure 6a shows olivine grains in plane-polarized light; Fig. 6b shows the same field of view in cross-polarized light. Each grain shows several interference rings, indicating that the birefringence is relatively high. The high birefringence helps distinguish olivine from quartz, although quartz also has a much lower refractive index; the refractive index can be difficult to

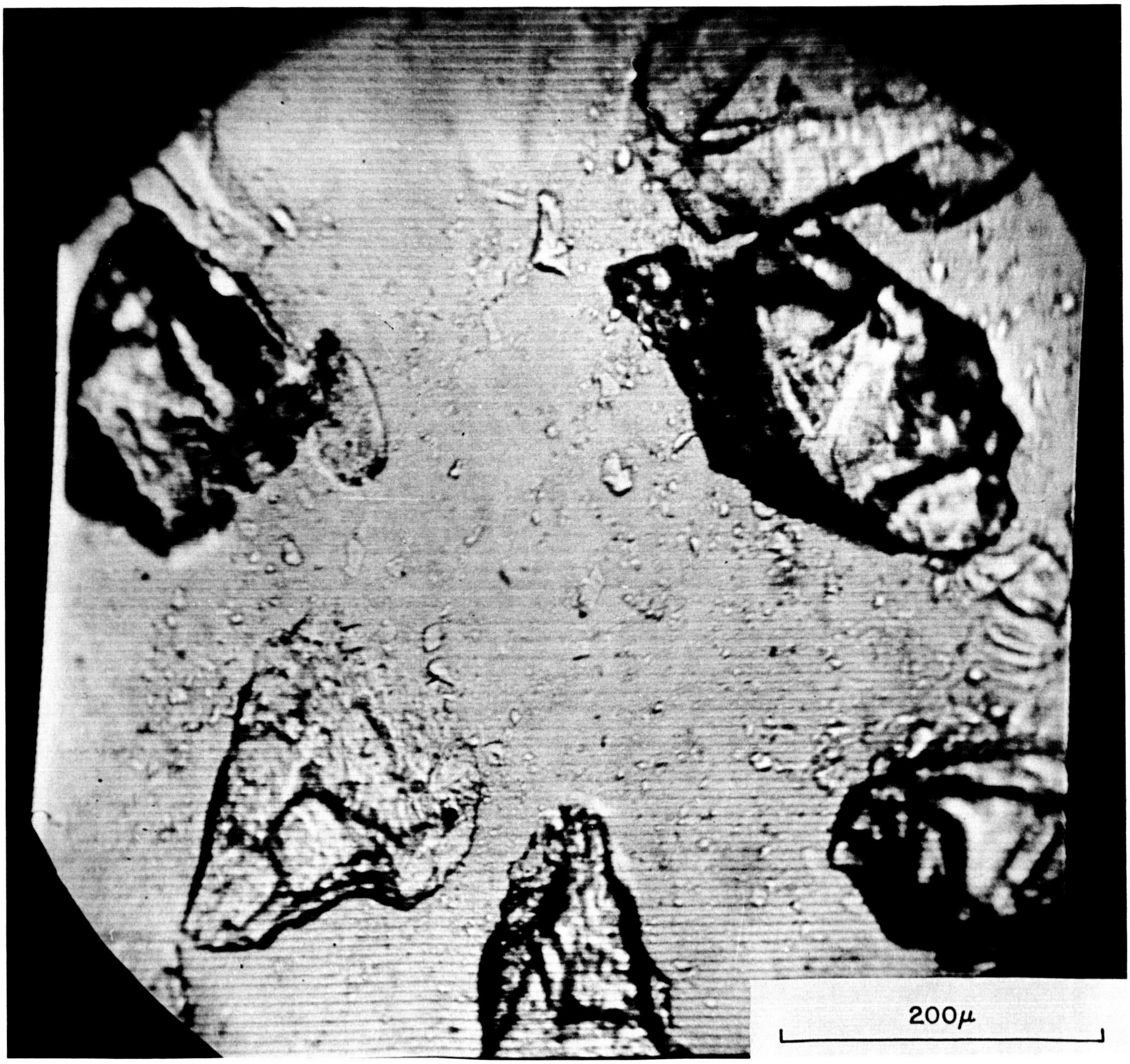

Fig. 6a. Twin Sisters dunite, plane-polarized light

judge in finer grained samples and the use of birefringence could help to resolve the ambiguity.

G. Glass Detection and Composition

The detection of glass is of importance because it will show that melting has occurred near or at the surface of the planet. The melting could either be from internal volcanic activity or external impact; that ambiguity is especially important on the Moon. Volcanic glasses probably will contain well-formed crystals of minerals whose compositions are consistent with the composition of the glass—for example, sanidine, quartz, or plagioclase phenocrysts in a siliceous lava. Impact glasses probably will have either no crystalline material as is the case for tektites, or else they will have irregular fragments of partially melted grains.

Isotropic grains with conchoidal fracture or pumiceous texture will almost certainly be glass fragments. They

Fig. 6b. Same field of view as Fig. 6a, cross-polarized light

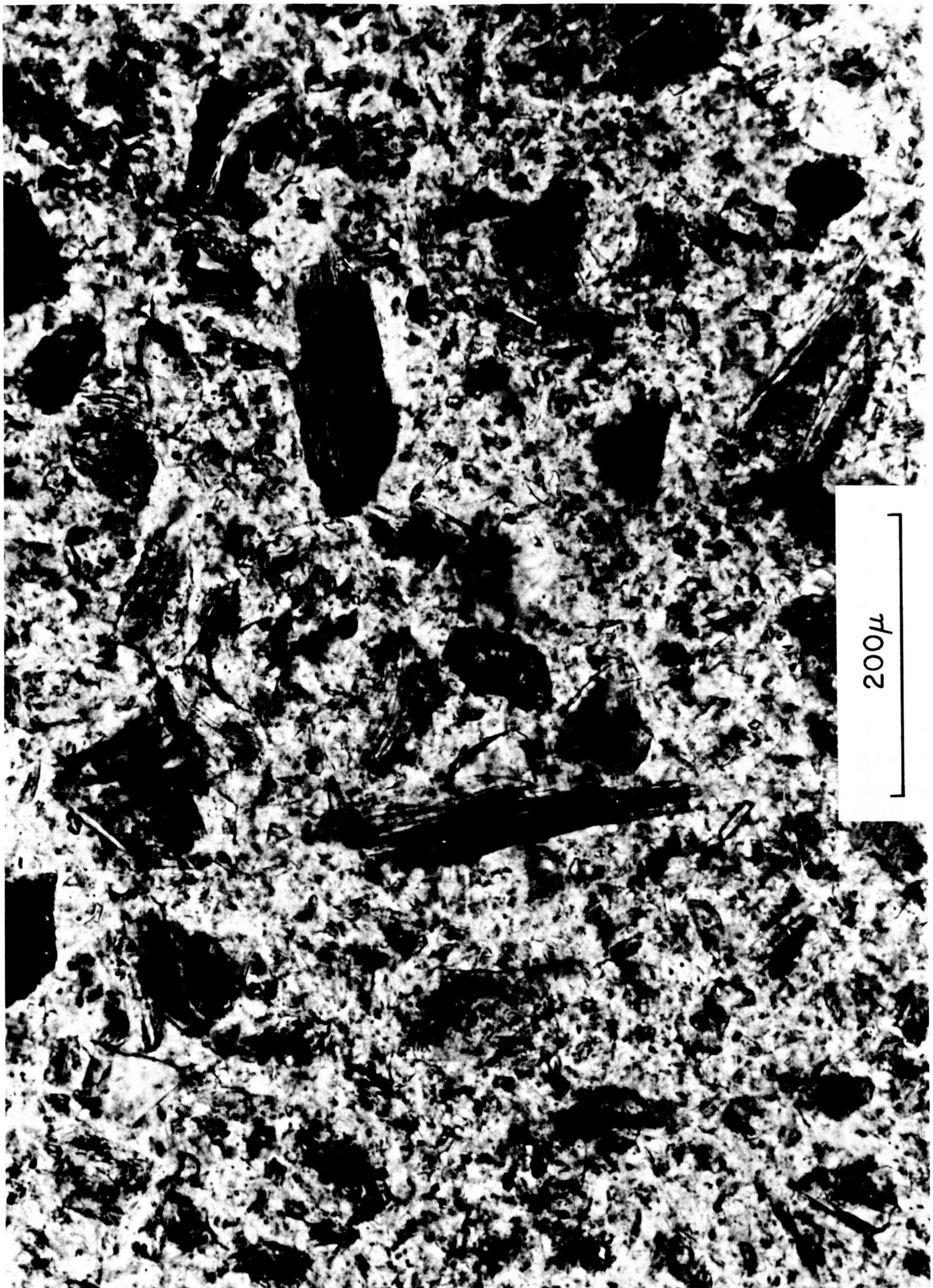

Fig. 7a. Bishop rhyolite tuff, plane-polarized light

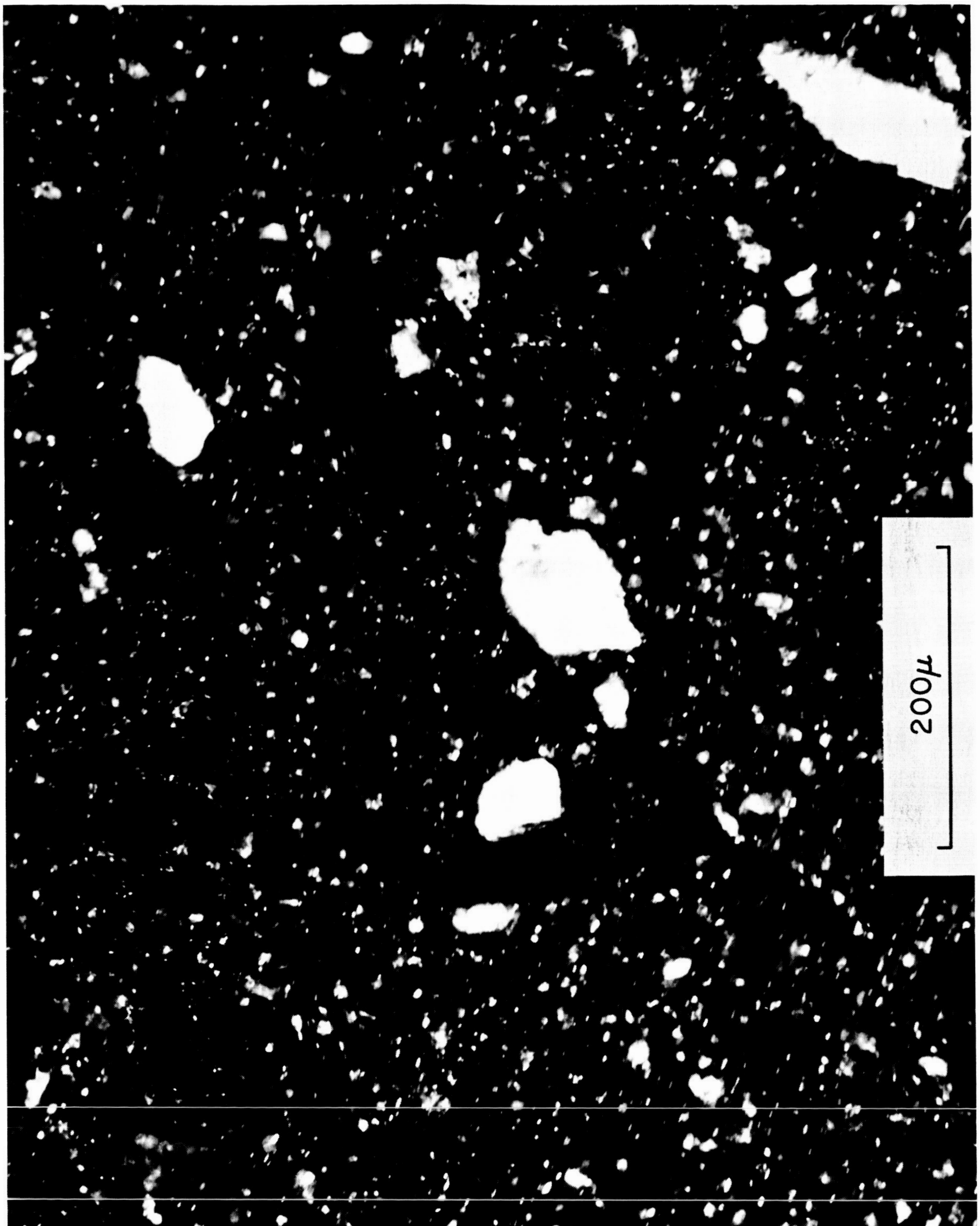

Fig. 7b. Same field of view as Fig. 7a, cross-polarized light

will be shown to be isotropic by the fact that they darken completely in cross-polarized light.

Figure 7a shows crushed fragments of the volcanic Bishop rhyolite tuff in plane-polarized light. The pumiceous texture of most of the fragments is quite obvious. Figure 7b is the same field of view in cross-polarized light; most of the particles are isotropic and therefore glass. The identity of the crystalline particles is uncertain from the photomicrograph, but the refractive index close to that of the mounting medium and the irregular fracture suggest that most are quartz.

An estimate of the composition of a glass particle can be made by judging its refractive index (Fig. 8). The refractive index relative to that of the mounting medium can be estimated by the Becke line technique. Mafic glasses, for example of basaltic composition, have refractive indices of about 1.58. Highly differentiated siliceous (including tektites) and alkalic glasses have refractive indices of about 1.48. The refractive index of the thermoplastic is 1.54, nearly midway between these extremes.

Figures 9a and 9b show glass particles at two levels of focus. In Fig. 9a the Becke lines are inside the edges of the grains; in Fig. 9b the Becke lines are outside of the grains and in the mounting medium. Figure 9b was taken at a higher level of focus than 9a; the refractive index of the glass is therefore below 1.54. The actual amount that it is below 1.54 must be estimated from the

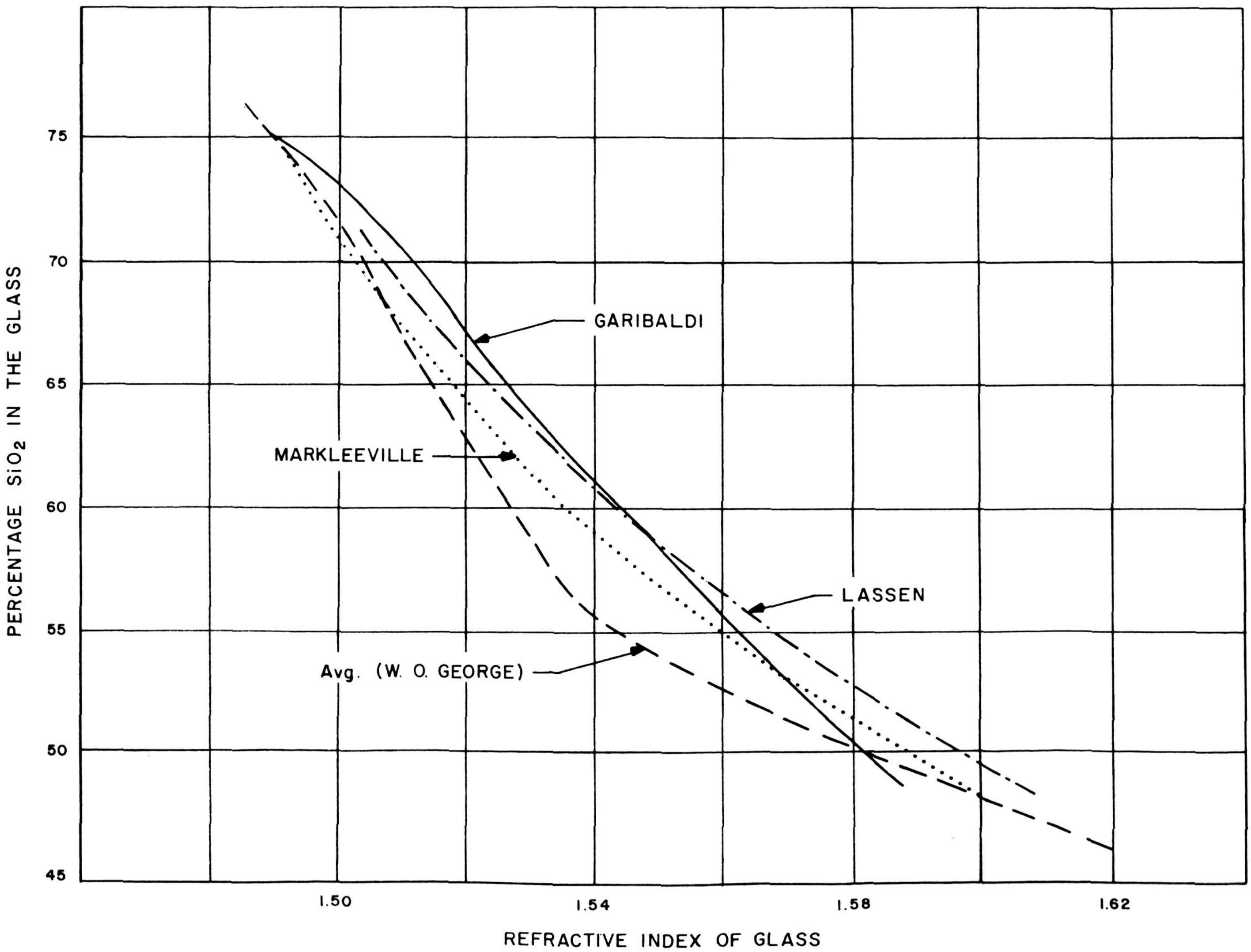

Fig. 8. Relation between refractive index and silica content of natural and artificial suites of volcanic glasses *(from Ref. 3, p. 28)*

strength of the Becke lines. The strength of the lines is a function of the difference in refractive index between the particle and the mounting medium, the angle of convergence of the light below the particle, and the geometry of the edge of the particle. In this particular case, in which the glass has a refractive index of 1.51, the Becke lines are easily visible.

H. Particulate Surface Material

A layer of particulate surficial material may overlie the bedrock at the surfaces of the Moon or planets at any landing point. In fact, if bedrock is considered as hard crystalline rock, it may not exist at all over most of the Moon; the rocks over much of the lunar surface may be either the original particulate grains from which the Moon was accumulated or they may be volcanic ash.

As described in Section III-B, it would be desirable to separate the material in the 0- to 60-μ range from the 60- to 300-μ grains. The finer sized particles are of lesser textural and mineralogical value; their size and shape distribution may be of considerable interest, however, and the two size fractions should be examined separately. The sub 60-μ fraction may contain the bulk of the micrometeorites, for example; the size-frequency distribution, shapes, and mineral species of micrometeorites are almost entirely unknown because such particles are quite difficult to identify on Earth. Micrometeorites on Earth are mixed rapidly with other materials by wind and water; the ferromagnesian and free metal micrometeorites are also rapidly weathered chemically to clay minerals and soluble ions. These destructive processes occur also, but to a lesser extent, on Mars, but not on the Moon.

Determination of the shapes of small grains may be important in order to separate fine particles into genetically distinct categories. An optical magnification of 25X should allow determination of the shapes of 10-μ particles and a magnification of 50 to 100X should allow observation of particles 5 μ or less diameter.

1. Particulate Materials on the Moon

If micrometeorites have essentially the same bulk mineralogical composition as stone meteorites, they should be easily separable if the lunar maria are filled with differentiated volcanic rock types, for example the basalt-rhyolite family. If the lunar highlands consist of ultramafic rock, perhaps the original materials from which the Moon was formed, it may be impossible to identify micrometeorites separately from highland ejecta. If the micrometeorites in a near-surface lunar sample can be identified, the relative volume fractions of the meteorites in samples from different places on the surface will show the relative ages of the surface deposits.

A particulate sample from the surface of the Moon, then, should consist of a main fraction from the bedrock in the immediate area, a micrometeorite component, and small components of ejecta from nearby small impact events or large impact events along their rays. By integrating information derived from different landing points we might be able to show differences in subjacent rock type from point to point, identify the main types of micrometeorite particles, and estimate the relative ages of the surface mantle deposits by comparing the relative proportions of micrometeorites in each sample—samples of the same age should have the same proportions of micrometeorites. It might also be possible to identify minor proportions of the sample with certain impact events if the landing points are in areas of clearly discernible rays from large craters.

2. Particulate Materials on Mars

Particulate materials on Mars should be more like those on Earth than those on the Moon. Mars may or may not have had oceans at one time, although liquid water probably does not exist on the surface at all at the present time. If bodies of water did exist, then Mars will have sequences of aqueous sedimentary rocks near the surface; a major proportion of the uppermost strata should be evaporite minerals, salts of the very soluble ions. Examples are $CaCO_3$, $CaSO_4$, NaCl, KCl, Na_2CO_3, $MgSO_4$, etc. These minerals are all soft and all have good cleavages, meaning that they should break up readily into fine sand and silt-sized particles; a major component of the frequent dust storms on Mars may be particles of soluble salts. These will be intermixed with volcanic materials if Mars has had much internal melting, with clays or other weathering products of the igneous materials, and with meteoritic debris. The reddish color of Mars' surface suggests that a ferric oxide may be plentiful but it is not known if it occurs in discrete particles or as coatings on silicates.

One further point about Mars is that a surface sample may contain organic or other biogenic material. Recognition of organic forms as distinct from inorganic forms is not always easy and many organic forms are quite small. The option of using high magnification, as outlined in Section III-B, may be very helpful in this regard.

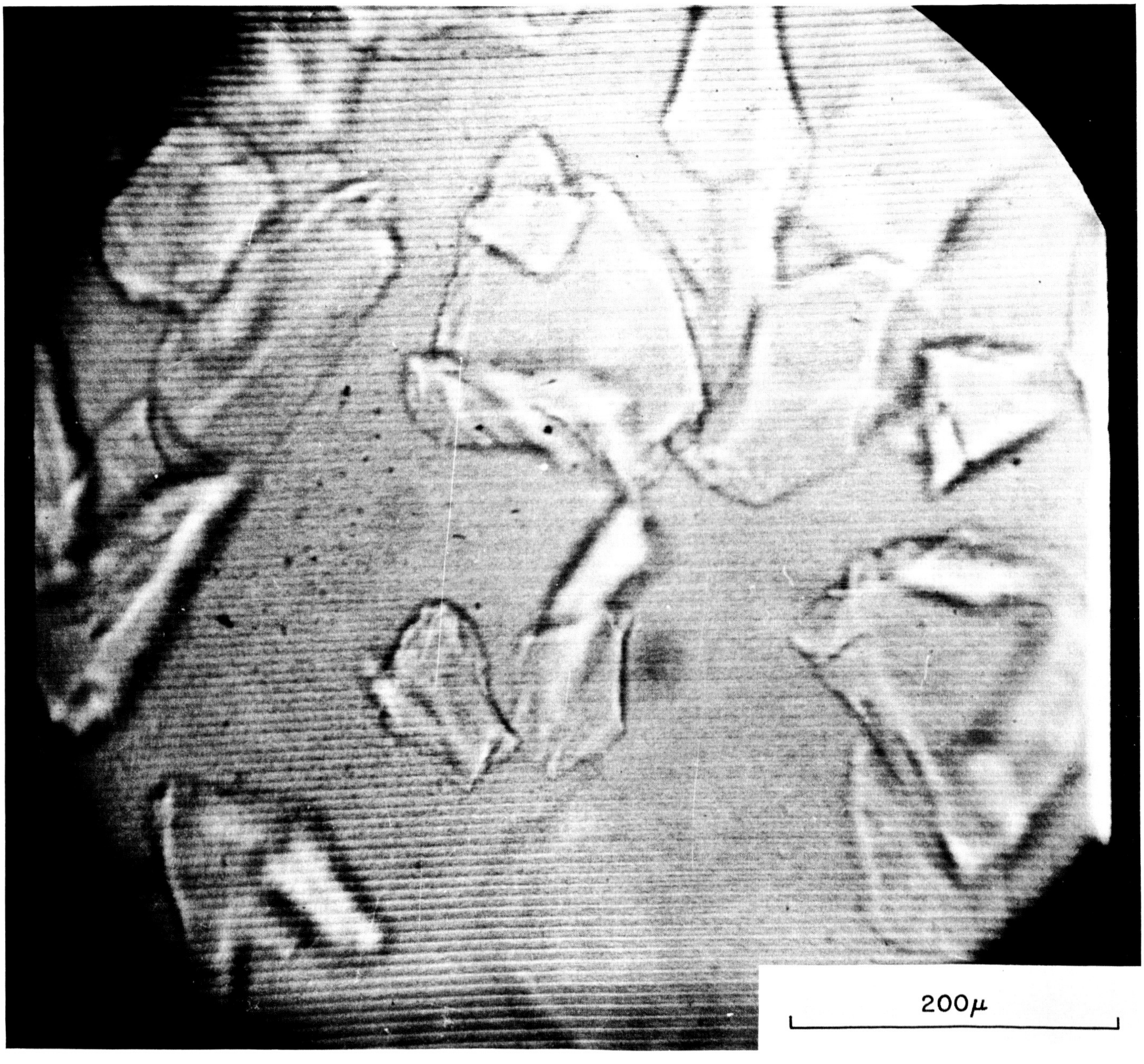

Fig. 9a. Glass particles, plane-polarized light

Lens positioned just below plane of sharp focus. Becke lines are within the edges of the particles.

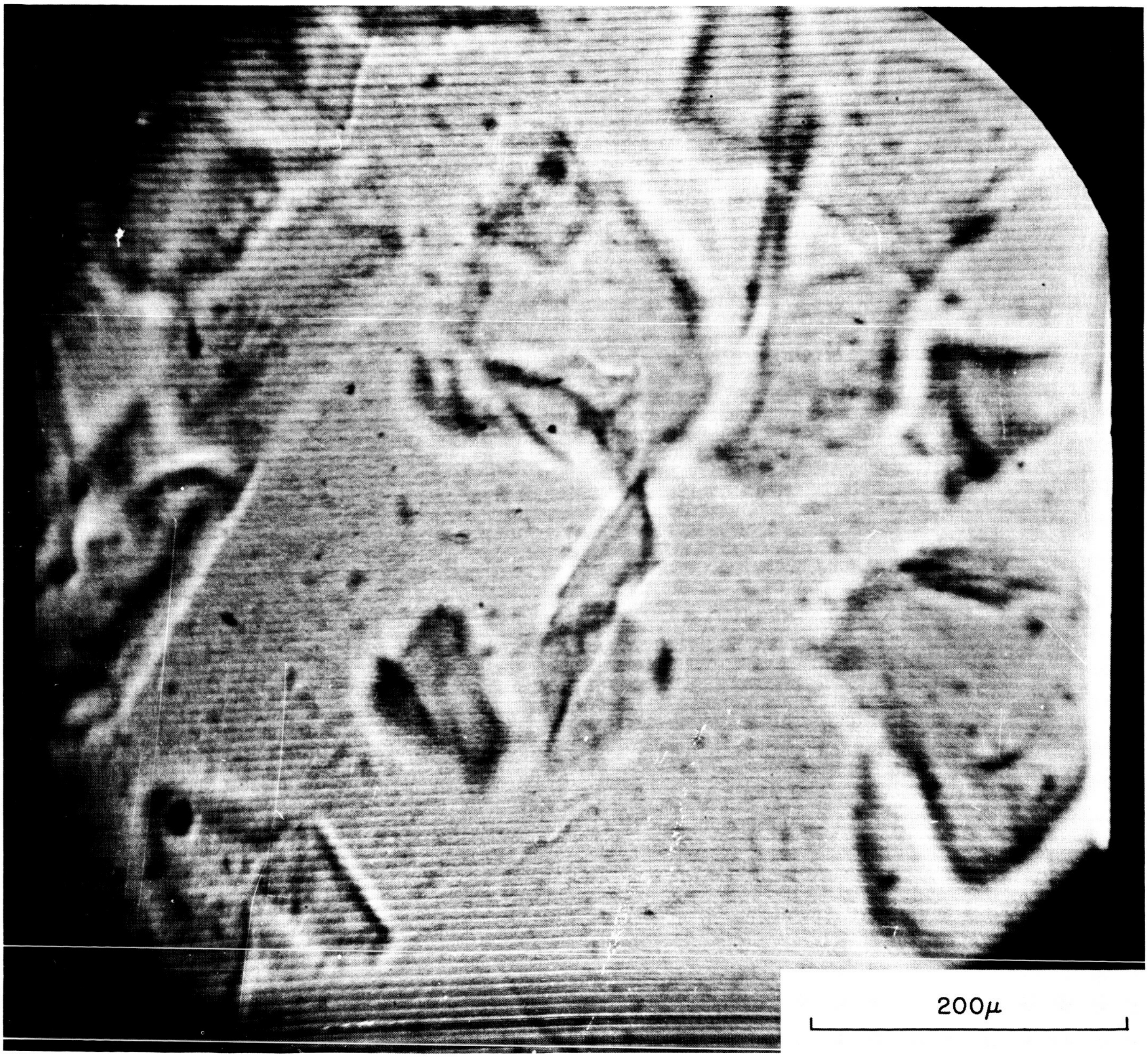

Fig. 9b. Same field of view as Fig. 9a

Lens positioned above plane of sharp focus. Becke lines are outside of the particles.

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